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What economic support is needed for Arctic offshore wind power?

Olli Salo [1], Sanna Syri *

Aalto University, Department of Energy Technology, School of Engineering, P.O. Box 14100, FIN-00076 Aalto, Finland

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ABSTRACT

Wind power is increasingly being installed in cold climates and in offshore locations. It is generally recognised that installing wind power to offshore locations is more expensive than onshore. The additional challenges from Arctic conditions with annual sea icing are still poorly known. We reviewed the existing knowledge of offshore wind power costs and developed a calculation model for the economics of offshore wind turbines in Finland, including taxes and sea base rent, to obtain a base case for determining the required tariff support. The model was tested with different production and cost rates to obtain a tariff price, which would make offshore wind power on Finnish territory economically viable for the producer. The main developers of planned offshore projects in Finland were interviewed to obtain a comparison between the created model and industry expectations. The cost of erected turbines was estimated to be 2750 €/kW. With this cost of capacity, it was clear that a higher than the current tariff price (83.5 €/MWh) will be required for offshore developments. Our analysis indicated a price level of about 115 €/MWh to be required. We found that even rather small changes in cost or production rates may lead to excess profits or economic losses and further research and pilot projects are required to define a more reliable tariff level.

Contents

* Corresponding author. Tel.: +358 50 599 3022.
E-mail addresses: olli.a.salo@aalto.fi (O. Salo), sanna.syri@aalto.fi (S. Syri).
[1] Tel.: +358 44 5092976.

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1. Introduction

Wind power is increasingly being installed in cold climates and in offshore locations [1,2]. Europe is currently the leading region in offshore wind development, mainly due to the significant activities in the UK, Denmark and the Netherlands [2]. Recently, two of the world's largest offshore wind farms were opened off the UK coast, the 500 MW Greater Gabbard farm and the 630 MW London Array farm [3].

It is generally recognised that installing wind power to offshore locations is more expensive compared to onshore. However, the additional challenges and costs from Arctic conditions with annual thick sea ice, pack ice formation and icing on surfaces are still poorly known. These are the conditions in many parts of the Baltic Sea, whereas, for instance, at similarly high latitudes on the Atlantic coast the ocean rarely freezes.

At the EU level, support for renewable energy is driven by the EU RES-directive, which targets to a 20% share of renewable energy in energy end-use by the year 2020. The RES-directive has varying national goals for each member state depending on the amount of renewables already in use. The goal for Finland is a 38% share of renewable energy in end consumption, which requires an increase of over 30 TWh to annual renewable production. As a part of this goal, The Finnish Government Long term climate and energy strategy dated November 2008 specified a wind power target of 2500 MW in Finland by the year 2020 and in 2011 a feed-in tariff came into force [4]. In Finland, there is a strong interest to start developing offshore wind power in addition to onshore projects. A total of 3000 MW of offshore projects are under investigation or preparation. However, there has not been any separate offshore wind power tariff, and it is very unlikely that offshore projects would be realised without a separate, higher support.

Among the industry, different opinions can be heard of the wind goal being achievable without erecting offshore turbines. Realisation of onshore wind power has been unexpectedly slow in Finland despite the large number of projects under planning and licensing (about 320 MW realised out of total 11,000 MW under planning) [5]. Projects are delayed mainly due to slow licensing processes and the treatment of local complaints against the plans. In favour of offshore turbines is the free space over sea, where turbine noise does not disturb habitants. In the 2013 update of the Energy and Climate strategy the government reserved 20 M€ for the first offshore wind power demonstration project [6]. The main objective of this paper is to answer the question "How much subsidies the Finnish offshore wind production would require to be economically viable?"

This paper estimates the investment costs for offshore wind energy in Finland. It introduces a net present value (NPV) model to estimate the required feed-in tariff prices for generated electricity to make such developments economically attractive for investors. The paper consists of three main parts. Chapter two estimates the costs of building an offshore turbine and connecting it to the grid. Research methodology and main sources are described in chapter three. Chapter four presents the NPV calculation model and parameters used in the model. Chapter five presents the results of the calculations and sensitivity analysis for selected parameters. Chapter six presents the results of a survey made for the Finnish wind power industry about their expectations and concerns. All background data in this paper have been gathered from literature sources, from the Finnish Wind Atlas and from the Finnish Wind Power Association web pages [5,7].

For simplicity, all calculations have been made for 3 MW turbine units as a part of a wind park and the possible economies of scale for increased plant size have not been taken into consideration.

2. Costs of offshore wind energy

Offshore wind production is based on the same technology and physical principles as onshore wind. Despite that, the costs of wind developments on land and sea are very different. The main offshore components can be considered as conventional machinery and structures but the harsh environment at sea sets more strict criteria to equipment and the construction of the foundations [8].

Other challenges arise with the operation and maintenance of the turbines, especially on the northern Baltic Sea because of annual icing of the sea and winter conditions. The whole offshore industry is rather new technology and none of the large-scale offshore parks in Europe have been in use for more than a decade. Hence, there is no first-hand information available on the actual life-cycle costs including decommissioning. The cold climate of Finland creates a problem with blade icing. Icing reduces production and mitigation measures like blade heating increases the costs of the turbines and increases the internal energy use in turbine. Unfortunately no cost estimations were found and icing was excluded from calculations. All these specialties affect the cost structure and its accuracy and they are discussed in this paper.

2.1. Basic offshore wind technology

The main structures and mechanical components of an offshore wind farm are foundations, tower, blades, shafts and gearboxes. For energy conversion to electricity there are generators, converters, transformers, cables and medium-voltage gas-insulated switchgear inside the turbine unit. In a wind park other electrical structures and equipment are substations for collecting produced electricity and stepping-up voltage. Subsea transmission lines are needed to evacuate power to the mainland grid [8].

Modern onshore turbines stand on tubular towers, mostly due to aesthetic purposes. For offshore farms located over the horizon, cheaper lattice towers could also be used. For instance, based on the environmental impact analysis of Merituuli Oy for the Inkoo Raasepori project off the South Coast of Finland, there are two available tower and foundation structures to be used on the Gulf of Finland. For towers the possibilities are tubular and lattice towers. Lattice towers are lighter and therefore require less steel but on the other hand require greater foundations area and are considered "old fashioned" by their looks. Tubular towers generate

a greater windshadow to the blades, but they can be better adjusted to the landscape by painting [9,10].

Foundations are divided to caisson- foundation and monopile-foundation. On the Gulf of Finland, as in the planned Inkoo Raasepori park, the more common monopiles can be based on bedrock. On the Bothnian Bay, foundations cannot be mined to the bedrock because of a thick layer of soft sediments on top of the seabed. Therefore the more expensive caisson-foundation is preferred there [11].

2.2. General cost structure

In the literature costs of a wind power project are usually divided into three main categories, but used categories vary between studies. According to Madariaga [8], the main categories of the life-cycle costs are investment costs, operation & maintenance (O&M) costs and network connection costs. National Renewable Energy Laboratory (NREL) divides the costs to capital investment, O&M costs and capital costs. Both methods can be used, depending on which part needs to be highlighted. The NREL system highlights the importance of capital costs in the project and Madariaga's system can be used when comparing projects where network connection costs fall differently to offshore wind farm (OWF) developers, depending on the national regulation [8,12].

Network connection costs in Finland are the costs of the transmission line to the closest onshore grid, which is operated by Fingrid, the Transmission system operator (TSO) in Finland. Connection is engineered together with Fingrid, but the power plant operator is responsible for all costs of the connection, including fault protection. Cost of electrical connection in Finland was not available for this paper and therefore the NREL cost model has been used with country-specific additions to O&M costs, including income taxes, real estate taxes, seabed rent and balancing cost. Capital costs are discussed in chapter 4 [13].

2.3. Operation and maintenance costs

O&M costs consist of normal operation costs during the whole life cycle of the turbine. These are salaries for maintenance staff, spare and repair parts, maintenance of electric installation, equipment required for maintenance and cost of not supplied energy during faults. Blanco [14] estimates the O&M costs to be up to 30% of the overall costs whereas NREL estimates them to be 20.5% [12]. This rather great variance can be explained by the different methodologies in calculating and allocating total costs, but also indicates the existing high variation between the estimated O&M costs. O&M cost estimates of European Commission (EC) [15], The Technical Research Centre of Finland (VTT) [16] and EWEA and are listed in Table 1 below. VTT projected offshore turbines economical parameters as a part of the work of a professional council to determine the reasonable feed-in tariff for onshore turbines. The report was funded by Ministry of Employment and the Economy (TEM), and the report called Proposal of Wind Power Feed-in Tariff in Finland was published as a result of the study (later PWPT report) [16]. It gave an estimation of 75 €/kW/a, which has been also used in this paper. For comparison, EWEA figures in the table have been scaled to different production rates from the given 16 €/MWh. A 5 €/kW/a difference in O&M costs, as between [15] and [16], would yield about 100,000 € change in the NPV with our calculation parameters for the 3 MW plant.

2.4. Total investment costs

Investment costs include all costs between feasibility studies and commissioning of the plant. Two different estimates of the percentage shares of different costs are presented by NREL [12] in Fig. 1 and by Blanco [14] in Fig. 2. Cost proportions here present a typical offshore wind farm (NREL) and average of offshore projects in the United Kingdom commissioned before 2007 (Blanco).

In the literature a great variation can be seen between the proportional divisions of these costs. Some of it is related to different classification of the costs, but as these estimates are made from the data of actual offshore developments with varying depths, park structures and layouts, distance to shore etc., some variation is natural. In both references, the turbine is about one-third of the total investment. With onshore developments the turbine cost increases significantly, usually two-thirds or more. Other main investment cost components are foundation and electrical infrastructure.

Snyder and Kaiser have collected realised costs from various projects on Baltic Sea and North Sea but state that costs are gathered from developer websites and cannot be independently verified. [9] The different announced costs are presented in Table 2.

EWEA predicts the capacity costs to decrease from the 3000 €/kW at 2011 down to 1500 €/kW by 2020 [19]. During the period 2000–2010 the costs increased unexpectedly, up to 3000 €/kW at 2010 for offshore wind farms (OWF). Part of this development

Table 1
O&M costs presented in various sources in €/kW/a [15–17].

	Min	Max	Reference
European Commission	71	105	80
VTT			75
EWEA (9000, 13,000, 11,000 MWh/a)	48	69.3	58.6

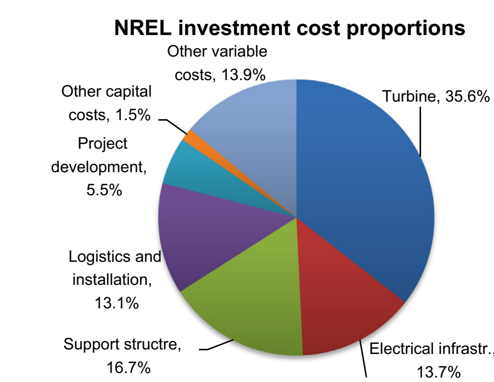

Fig. 1. Proportional shares of investment cost components by NREL (without O&M costs) [12].

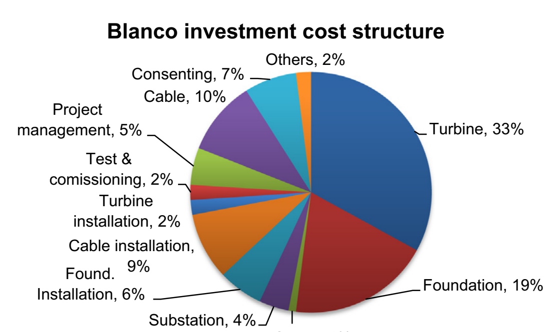

Fig. 2. Proportional shares of investment cost components by Blanco [14].

Table 2
Investment costs of European offshore wind farms. Costs converted to euros from USD [9,18].

Name	Country	Year constructed	Capacity [MW]	Depth [m]	Turbine size [MW]	Distance to shore [km]	Total cost [M€]	Cost [M€/MW]
Kentis Flats	UK	2005	90	5	3	10	147.54	1.639
Barrow	UK	2006	90	17.5	3	7.5	129.18	1.435
Egmond aan Zee	NL	2006	108	18	3	10	227.09	2.103
Burbo Bank	UK	2007	90	5	3.6	6.5	125.78	1.398
Beatrice	UK	2007	10	45	5	22	47.59	4.759
Lillgrund	SWE	2007	110	7	2.3	10	203.97	1.854
Q7	NL	2007	120	21.5	2	23	401.14	3.343
Inner Downsing	UK	2008	90	9.5	3.6	5	407.94	4.533
Robin Rigg	UK	2008	180	5	3	9	520.13	2.890
Throton Bank	BE	2008	300	14	5	27	849.88	2.833
Average			118.8	14.75	3.35	13	306.02	2.679

Table 3
Investment cost estimates and predictions in €/kW from various sources. Costs are given as range if given in source, other values are marked in Max column.

Min [€/kW]	**Max** [€/kW]	**Reference source**
1800	2500	Blanco 2008 [14]
	2300	Green, Vasilakos, 2011, data from 2009 [21]
	3592	Heptonstall (Converted to $€_{2009}$) 2011 [20,22]
	1930	Comparison of electricity production costs in Finland, 2012 [23]
1750	2750	EU Commission, 2008 [15]
	2500	PWPT-report, 2009 [16]
	2882	Inflation-corrected (2012) average from *Table 2* [24]

(2005–2008) can be seen also in Table 2. Madariaga [8] states that the costs have increased until the end of the last decade, but are now reducing [8]. Predictions have been made about cost increase continuing further to the present decade. Currently, it seems like the cost increase has turned down and a ‘normal’ learning curve has returned. The main reasons for the increase in prices were a surge in turbine supply, the increasing costs of raw materials, commodities and labour used in turbine manufacturing and also the demand for larger turbines and stronger structures compared to those seen before. The key materials for turbines are steel, copper, carbon fibre, lead, cement and aluminium. Table 3 presents the other available estimates and compares them with the average of Table 2 estimates [14,20].

References in Table 3 have been presented for 2008–2012 and give a cost range of 1750–3592 €/kW. As can be seen in Table 2 the costs can vary significantly even during a single year, based on the depth of project area and distance to shore. The projected offshore sites in Finland are located on semi-shallow waters, ranging from 5 to 20 m in depth. Given the problems with icing on Finnish waters, it is not likely that investment costs in Finland would be in the lower end of the range, but neither in the highest end due to moderate depth and distance to shore [7].

The value for the base case was selected to be 2750 €/kW, as estimated by the EC. This value would also represent the estimation of EWEA for a project commissioned during 2013.

3. Research methods

Research material consists mostly of scientific articles published during the past five years. These were selected in order to obtain the most accurate cost information, especially as it was known before starting this project that modern large-scale offshore wind parks were not developed before 2005. An additional reason for gathering as new as possible cost data was the unpredicted 20% increase in turbine costs during the period 2005–2008 [14].

As the key elements of the cost analysis were found from peer-reviewed literature, the suggested function and parameters were tested in this work. A base case for the investment was constructed with the data used by VTT/TEM for defining the tariff support for onshore wind turbines. These parameters were then adjusted to the characteristics of offshore wind and tested with varying investment costs, annual production and cost of electricity to see how they would meet the requirements of investors.

The wind resources of planned wind park locations were assessed. Wind Atlas, provided by the Finnish Meteorological Institute, was used to evaluate wind resources on planned project sites and to get estimations of production [7]. The likely production of the sites was calculated with two different methods; first by averaging the production of existing Kemi Ajos turbines located on artificial islands close to the mainland in the northernmost part of the Gulf of Bothnia, as they are the closest comparison in Finland to existing offshore turbines. Second, Wind Atlas production estimates were gathered for three planned project sites along the Finnish coast and adjusted to Kemi Ajos historical data in correlation to Wind Atlas data from the same site.

As an independent part of the study, a survey was made to main offshore developers in the Finnish wind power industry. This was done to check whether or not our calculations and the actual industry expectations correlate with each other.

4. The NPV model

A cash flow statement was made to calculate the annual profits during the operational time of the turbine. Cash flows were then discounted to obtain the net present value of the investment. Items of income and expenditure reported in the cash flow statement are further discussed in this chapter.

4.1. Current policies and state support

Current support policy for wind power in Finland, including offshore wind, is defined in the act of production support for electricity produced with renewable sources. [25] The main terms of the support are:

- The power plant is new, has not received state support and combined capacity of generators is over 500 kVA.
- Target price will be paid to all producers accepted in the programme, until the summed capacity of generators in the programme reaches 2500 MVA.
- The plant location and grid interconnection are in Finland.
- Tariff price will be paid for electricity produced during a 3-month tariff period.

- Target price for wind power is 83.5 €/MWh.
- Target price will be paid for electricity produced in plants' generators, reduced with power consumed by the plant itself. Support will be paid by the TSOs meter reading at the interconnection point to the grid.
- Paid support will be the target price reduced with average market price of the 3-month period. If the average market price is under 30 €/MWh for the period, the tariff will be paid as target price reduced with 30 €/MWh.
- As an exception to the target price, an additional bonus feature was added for fast project development. New projects will be supported with a target price of 105.3 €/MWh until 31.12.2015, with a maximum time of 3 years with higher target price.

At the moment there is no additional support scheme for offshore wind power. If such support is deemed necessary, it is most likely going to be in a similar form as the current support scheme. Therefore this paper also concentrates on defining a 12-year target price scheme, which would make offshore investments economically viable. Another possibility for offshore wind power support is straight investment support. In the programme of the present government is written that the investment support will be continued to renewable demonstration projects, including offshore wind power [6,25]. Following the Spring 2013 update of the Government Climate and Energy Strategy, the government budgeted 20 M€ € for the year 2014 to support the first demonstration plant. The support money is additional to the normal feed-in tariff and it is to be used for covering the higher construction costs offshore and to reduce the investor's risk while trying to gather first-hand experience of offshore wind in Finland. A total of six companies applied with nine different projects, which will be evaluated and short-listed at the end of 2013 for the second application round. The proposed project sizes vary tenfold, and distances from the shore are 2–9 km [26].

Electricity taxation in Finland has had a support for renewable energy paid by consumers, which is 0.69 €cent/kWh for old facilities. For new facilities since 2011 tax reductions have been replaced by directly paid production tariff prices to producers. For the actual production of wind-generated electricity there is no tax, as there is no fuel consumption [27].

4.2. NPV model parameters

The main parameters of the cash flow statement, their ranges and values used in our base case model are discussed below.

4.2.1. Discount rate and lifetime

The selected discount rate (return on equity) for the NPV calculations was 10%. This percentage is used also in the PWPT report defining tariff support for onshore wind. Turbine economic lifetime was set to be 20 years, which is commonly used in the literature for offshore turbines and also suggested in the PWPT report. An assumption of a longer lifetime for offshore turbines can be found in some studies. Five years longer expected lifetime compared to inland turbines is mostly based on an assumption of less-turbulent winds and lower speed variation over turbine. This results in lower fatigue loads for blades and power transmission equipment and therefore could lengthen the lifetime, but has not been proved in practice and is not considered in this paper [16].

4.2.2. Annual production

The annual production estimates for existing offshore wind were derived from the historical production data at Kemi Ajos' existing wind park. Used data was the production of the year 2010 and because of lower than average wind speeds during the year in question, the data was multiplied with a correction factor of 1.351 (100/74). Corrected average annual production (AAP) for Ajos T4 – T11 was then found to be 9788 MWh/a. Ajos is the only wind power development in Finland to be considered as an offshore park, but by location it could also be classified as coastal [28].

Ajos production was compared to the production estimates from Finnish Wind Atlas for a 3 MW turbine at a nacelle height of 100 m. This gave an estimate of the relationship between historical data and Wind Atlas data. For the Ajos site, historical average production was 97.9% of the Wind Atlas estimate [5,7,28].

The Wind Atlas was then used to assess three planned offshore parks, i.e. the Inkoo Raasepori, the Raahe Maanahkiainen and the Ii Suurhiekka areas. Estimates can be seen in Table 4. The Ajos turbines are built on artificial islands close to the mainland and therefore do not fully represent the production possibilities of offshore wind power. For this reason the mentioned projects were selected to represent true offshore parks. For the base case annual production an average of the corrected production estimates was calculated and compared with the PWPT report estimate. The mean value of these two estimates was 10,991 MWh/a, which was rounded up to 11,000 MWh/a for the base case. NPV calculations with annual production between 9500 and 12,000 MWh/a can be found from the sensitivity analysis of results provided in chapter 5.

4.2.3. Balancing cost

Balancing cost is paid by the energy producer to cover the costs of generation capacity reserved and used to balance the production when the producer is not delivering the power sold in the Elspot previous auction. As wind production cannot be forecasted perfectly, it has a higher prediction error and requires more balancing capacity compared to conventional coal or gas-fired generation. In Finland, wind producers are responsible for their balancing costs. The PWPT report suggests a balancing cost of 2 €/MWh produced by wind turbines [16]. Similar values have been given by Holttinen et al. [29]. In Finland the increase in balancing cost with a wind penetration level of 10–20% of gross demand would be between 2 and 3 €/MWh. In this paper, the value of 2 €/MWh was used through all calculations.

4.2.4. Loan terms

Wind power developments are upfront cost projects, where the majority of the costs occur before any income is gained. The interest of loan capital is usually much smaller than the cost of own capital and therefore developers tend to push the loan proportion of the investment as high as possible. According to the PWPT report, banks are usually not willing to loan more than

Table 4
Wind Atlas production estimates for 3 MW turbine for the selected project areas and data correlated to the Ajos plant realised production.

	Wind Atlas, 3 MW annual average production [MWh/a]	Corrected to Ajos data [MWh/a]	Full load hours per year [h]
Inkoo, Raasepori	13,030.5	12,755.3	4252
Raahe, Maanahkiainen	11,508.4	11,265.3	3755
Ii, Suurhiekka	12,489.1	12,225.4	4075
Ajos T4 – T11	9999	9787.8	3263

70% of the investment. The main cost of capital comes hence from the interest rate of the loan, which is affected by the bank margin and the general cost of capital on the financial market. Banks set the margin for the loan depending mostly on the risks of the project. In well investigated and prepared projects in Europe the margin has been 2–3% [16].

After the financial crisis in the autumn of 2008, the European Central Bank has been maintaining an interest rate at a low level (0.75–1.5%) to boost investments. This has secured a low interest rate for industrial projects. In this study, a rate of 5% has been used as base case and a sensitivity analysis is presented in chapter 5 [30].

Loan was assumed to be annuity-based loan, meaning equal payments during the whole loan period. The EC states the construction period to be two years, but as it was not clear what kind of payment agreement the developer would have with the contractors and bank it was assumed that the loan would be cashed in the end of year 0 and paid back always at the end of the year, starting at the end of year 1, the first year with production [15].

4.2.5. Tariff support period

The incomes of the wind project depend mainly on three factors: the wind resources on the site, electricity price on the market and tariff support. Uncertainty of future incomes affects the loan margin; therefore, it has a significant impact on the economic feasibility and should be predictable as far as possible. Banks are usually unwilling to give loan for longer periods than the tariff support is given. In addition to this, investors are unwilling to invest in projects with payback period longer than 10–15 years. Therefore a full 20-year tariff period was not considered reasonable and the required base case tariff level was calculated for 12 years as in the PWPT report. For comparison, the required tariff level was calculated also for 10- and 15-year periods [8,16].

4.3. External costs of a project

A power plant development project will always have some external costs, which cannot be affected by the developer. These costs include permit and application fees during the project planning and development and are usually part of "Project development costs" as in the NREL cost model (Fig. 1). During the construction and operation phase of the project the owner has to pay land rent and real estate tax, which are set by the land owner and municipality authorities. These are further discussed below.

4.3.1. Rent of the seabed

Besides possible electricity feed-in tariff prices, the state can also affect offshore wind powers cost structure with real estate rental prices. Permit to rent out sea areas has been given to the National Board for Forests, which is administrating all sea areas in Finland. The renting is defined in the law concerning the surrender of state-owned areas. We inquired about the rental department of the Board, and they informed unofficially that the rent for offshore wind parks is planned to be bound to production as 0.75 €/MWh, indexed to the value of EUR_{2010}. As no actual offshore parks have been developed so far, the rental price has not been confirmed. Although the rent is not one of the most significant costs of a wind park, it has an effect on the investment profitability calculations. The Ministry of Finance sees that "The rent for offshore wind areas has to reasonable, to avoid unnecessary straining of the profitability of such investments." This statement indicates that the rent will be kept on a reasonable level also in the future [4].

4.3.2. Real estate tax

Real estate taxes have been projected based on the information given in the PWPT report. Real estate tax is applied to all power generation facilities with a rated power less than 10 MW. Tax is levied by the local municipality and can vary between 0.5 and 1.0%. Tax is not paid from the machinery in the investment and therefore the PWPT report assumes 20–40% of the investment to be taxed. We used the mean value of 30%. The PWPT report is concentrating on onshore facilities where the turbine may count up to 70% of the investment. As mentioned before, Blanco and NREL count the turbine, including main machinery, to be roughly 30% of an offshore investment and therefore the upper limit of 40% of investment is taxed in these calculations. The taxed value is reduced by 5 percentage points annually until reaching 20% of the original taxed value [16].

5. Economically viable offshore wind

This chapter presents the results of the NPV model described in the previous chapter and the results of the economical simulations with the model. It also presents the sensitivity analysis of key variables. These results are meant to be used for assessing the tariff support level for offshore wind. If the cost of offshore wind is to be compared with other forms of electricity production, a more reasonable mean**s** would be the levelised cost of energy instead of NPV, as e.g. Levitt suggests [31].

5.1. The base case and the current tariff

The base case was generated with economical parameters from the PWPT report and the current tariff support given to all new wind power in Finland to calculate what would be the maximum investment cost (€/kW) at the break-even point. Incomes are calculated with the Ajos and the Inkoo Raasepori annual average production (AAP) and presented in Table 5. Calculations have been fitted to the current support scheme, three years of the higher tariff (105.3 €/MWh) and following nine years with the lower tariff (85.3 €/MWh).

The current support is clearly not sufficient for economically viable offshore wind production. For coastal locations as Ajos it may be possible to reach a cost level of 1788 €/kW but for a fully offshore project as Inkoo Raasepori, it is not likely for developers to be able to push the costs as low as 2548 €/kW. It should also be noted that the Raasepori production rates indicate 4250 annual full load hours, which would be exceptionally high even for offshore locations.

The base case describes the economics of a project with the estimated average development costs and production rates described in the previous chapter. The tariff support has been adjusted so that NPV after 20 years will be 0. For simplicity the tariff has been rounded with single decimal to first positive cumulative NPV. We summarise the parameters used in Table 6, also including the parameters of the earlier government work for comparison.

Tariff period in the currently enforced scheme has been set to 12 years. The Base case model was also tested with 10- and 15-year tariff periods to find out the effect of the tariff period length on the tariff rate and the cumulative sum of the paid tariff. The required tariff was rounded off to single decimal and the

Table 5
Maximum investment cost with the PWPT-report parameters for the Ajos and Raasepori production rates (NPV 0).

Annual production [MWh/a]	Maximum allowed investment cost [€/kW] with present tariff level
Ajos 9788	1788
Raasepori 12,755	2548

lowest tariff with positive NPV is given in Table 7. Other parameters are as described in Table 6. Owing to the high discount rate of own capital, the cumulative undiscounted tariff paid increases with a longer tariff period.

5.2. Sensitivity analysis

The most important cost items defining the project economy, i.e. electricity price, investment cost and production rate, were given different values in order to see how the change of these values will affect the overall economy (NPV) of investment. Also the effect of the loan interest rate was analysed.

Table 6
Parameters of the PWPT report offshore model and base case of this report compared. In the PWPT column the cumulative NPV is calculated with our model presented in this paper.

Item	PWPT-report	Base case	Unit
Annual production [MWh]	9900	11,000	MWh
Economic Lifetime	20	20	Years
O&M	75	75	€/kW
Investment Cost	7,500,000	8,250,000	€
Share of own capital	30%	30%	
Share of loan	70%	70%	
Own capital	2,250,000	2,475,000	€
Loan capital	5,250,000	5,775,000	€
Bank interest	5.00%	5.00%	
Tariff (12 years)	118.9	114.7	€/MWh
Tariff (until 2015)	118.9	114.7	€/MWh
Electricity price	50	50	€/MWh
$P_{turbine}$	3	3	MW
Income tax percentage	28.00%	24.50%	
Real estate tax percentage	1.00%	1.00%	
Discount rate	10.00%	10.00%	
Balancing cost	2	2	€/MWh
Seabed rent	0	0.75	€/MWh
Cumulative NPV	10,173	310	€

Table 7
The base case model adjusted to NPV 0 with 10–15-year tariff periods.

Tariff period [years]	Cumulative NPV [€]	Tariff [€/MWh]	Cumulative tariff paid [€]
10	3220	121.8	7,898,000
12	310	114.7	8,540,400
15	2982	108.0	9,570,000

5.2.1. Variable electricity price

Since the opening of the Nord Pool Spot in Finland in 2000, the electricity price has had an annual average between 14.88 €/MWh (2000) and 56.64 €/MWh (2010) [32]. The price development has not been stable and linear, yet the trend has been an increasing electricity price. The comparison of profits between The Base case with annually increasing electricity price at rates of −1%, 0%, 1%, 2% and 3% was simulated but had no major effect on project economy. This is natural, as the electricity price risk in the current support scheme is shifted mostly to tariff payers from producers. Tariff support is defined by the difference between market and target prices and it evens out the fluctuation of market price as long as it is within the limits given in the current support scheme and the projected tariff price (30–114.7 €/MWh). In addition, incomes after the tariff period are heavily discounted, and hence have a much smaller impact on the project NPV than the incomes of the early years of the project.

5.2.2. Variable investment cost

Out of the three most important economic factors, investment cost is the most important and the only one the producer somehow can affect. As discussed, the tariff scheme protects the project economy from low electricity prices and the production rate cannot be increased to exceed climate constraints. Therefore the cost of capacity has to be well known in the feasibility study of an offshore wind project. As can be seen in Fig. 3, an increase of 10% in cost of capacity will bring the NPV down over 500,000€ for a 3 MW turbine. Similarly, the tariff scheme gives a possibility to make substantial profits. This is a built-in problem in a fixed-price tariff, where the target price is set to ensure that also the last project accepted to the scheme will be profitable.

5.2.3. Variable production rate

All incomes of a wind turbine depend on the electricity delivered to the grid. Produced electricity depends on the location of the turbine and nacelle height, which define the average wind speed over the turbine. Therefore it is one of the main concerns of a developer to find a location with as high as possible average wind speed and to be able to predict the future production as accurately as possible. Accurate wind speed measurements provide accurate income prediction and reduce the investor's economical risk and loan margin.

The effect of different annual production rates to the NPV is shown in Fig. 4. With costs estimated for the Base case of this

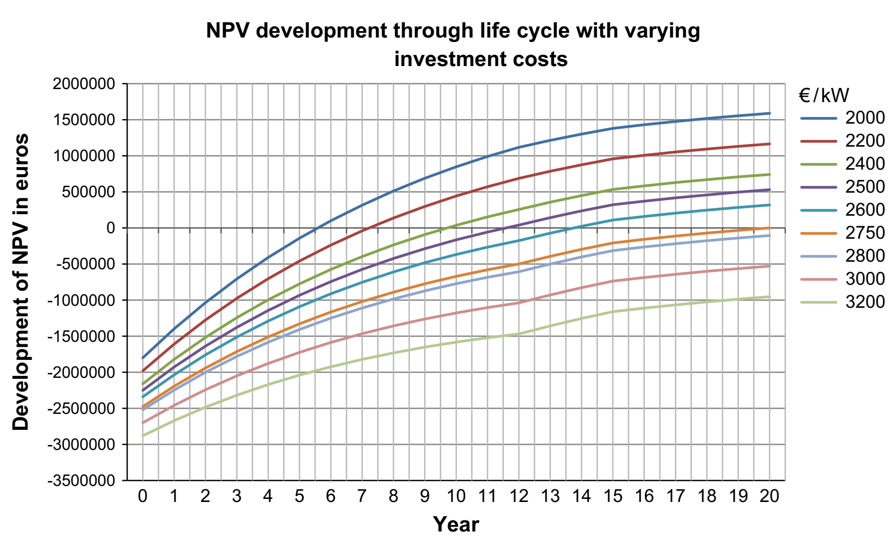

Fig. 3. Cumulative NPV development with varying investment cost rates [€/kW].

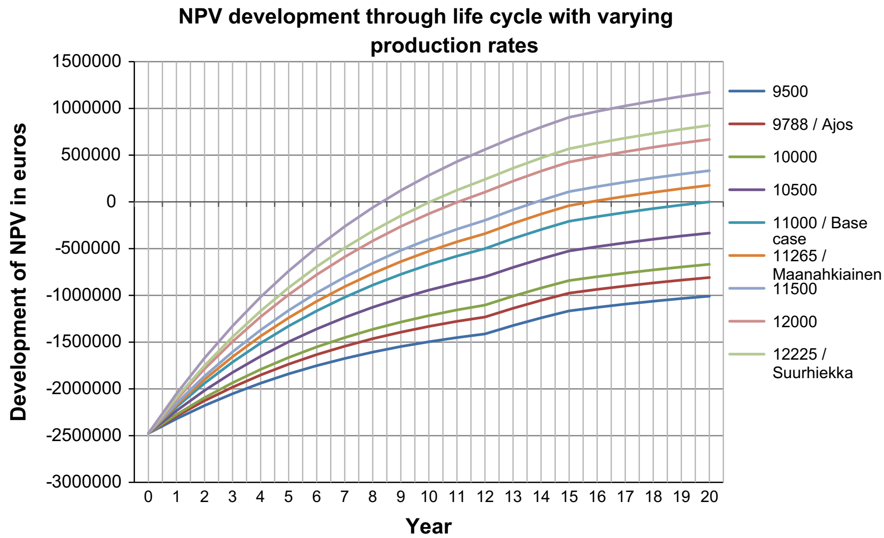

Fig. 4. Cumulative NPV with varying production rates [MWh/year].

Table 8
Base case cumulative NPV with different bank interest rates.

Interest rate	4%	4.50%	5%	5.50%	6%	6.50%
Cumulative NPV after 20 years [€]	187,107	94,434	310	−95,248	−192,221	−290,590

paper, the historical production rate at Ajos is far from an economically viable project. The Ajos-corrected Wind Atlas production rates of the three other considered project areas would be clearly profitable, if the investment cost can be kept under the assumed 2750 €/kW. This enforces the conclusion made before that projects located on best sites will be gaining substantial profits with a fixed-price support scheme. Comparison (Table 8) shows that 4.5% reduction (10,500 MWh/a) in annual production has a greater negative impact on project NPV than an increase of 1.5 percentage points in the bank interest rate.

5.2.4. Interest rate

The interest of bank loan is the main capital cost of a project. The interest rate is defined by the capital market and can change significantly in a rather short time. The loan is paid back during the first 12 years of production, which also have the greatest impact on economic success of a project. Therefore it was seen reasonable to test the model with different interest rates to see how great an effect it has for the cumulative NPV. If the interest rate of the loan is 1% lower or higher than in the base case, it results in a loss or profit of around 190,000 €, corresponding to 7.68% of the equity, as can be seen in Table 8.

6. Industry expectations

In order to get a comparison with our calculations presented in this study, we made a separate survey of the main Finnish offshore wind developers. A request to answer the e-mail survey was sent to individuals responsible for offshore projects in the following companies: Innopower Oy, Rajakiiri Oy, Suomen Hyötytuuli Oy, Suomen Merituuli Oy, WPD Finland Oy and Ålands Vindenergi Andelslag. The survey consisted of four questions with open answer fields. The following were the questions:

1. Does offshore wind require different economical subsidy from onshore wind power?
2. What sort of support would be the best? (Feed-in tariff, investment support, …)
3. How great and for how long would this support be required? (Compare with the present tariff of 12 years/83.5 €/MWh or XX €/MW)
4. Which other than economic factors hinder or block building offshore wind parks in Finland?

Out of the six approached companies four answered. The answers to separate questions were partly overlapping and some were more explaining the current situation of the industry in Finland than answering the original question. Answers are gathered under the corresponding question numbers in Table 9.

The answers reflected clearly the results of this study. As there is no first-hand experience of real offshore wind parks in Finland, it is hard to give any exact numerical values for the required support. There does not seem to be a consensus in the industry on the preferred support methods but only that the support has to be higher than it is now for onshore wind. Outside economic consideration, the main obstacles are different permits of using the seabed, issued by several different state authorities.

7. Discussion and conclusions

There is a growing interest to construct offshore wind power, also in challenging Arctic climates. In Finland, there are 3000 MW of offshore wind projects in at least the initial planning stage. It is clear that offshore wind in challenging cold conditions with a regular thick seabed ice, thick pack ice and icing on the blades requires higher tariffs than onshore installations. In this work, we made initial economic estimates of the required tariff levels. However, the economic implications of the actual problems occurring due to the climate conditions cannot be properly estimated a priori. We recommend a step-wise approach in the public support: a guaranteed feed-in-tariff valid up to a rather high upper limit of capacity, as was done with the present tariff in

Table 9
The compiled survey answers.

Question	Answers
1.	All answers were positive, two gave the argument that construction costs in Finland are 2–2.5 times higher compared to onshore, cabling and O&M costs are also higher; therefore a higher tariff is also required.
2.	One stated that investment support would be better for the investor; another stated that a higher feed-in tariff is required. Two remaining did not consider which one would be better but noted that both have pros and cons and the final support has to be decided depending on the support time etc.
3.	Only one numerical answer was given, which was 120–150 €/MWh but without duration. The rest considered that support has to be enough for covering the higher costs of construction and downtimes caused by ice and waves but numerical values are still under research. It was also stated that support should be based on the actualised costs as the basic technology is developing fast but very few projects have been made in similar ice conditions.
4.	Three of the answers saw the most significant problem to be the unclear, complex and overlapping procedures in permit application for constructions over state-owned seabed. One stated the major problem to be harsh weather conditions. Also permits considering naval and air navigation and defence forces were mentioned. In addition it was mentioned that the support money is partly circulating back as the seabed has to be rented from the state.

Finland, would not be an optimal approach. Rather, it is recommendable to initiate the first projects with, e.g., an open tendering process to gain actual operating experience, as is done now in Finland. Altogether nine projects with sizes varying tenfold, are competing for the 20 M€ demonstration support for the first Finnish offshore project. Distances from the shore are 2–9 km.

One of the main problems of this study was to find the actual data of offshore wind production on annually freezing sea areas. As no such data was available, additional costs for reinforced tower foundations were not used. This inaccuracy in investment costs might have a great effect on the overall economics of such installations which can be seen in the results with different investment costs. The cost of reduced production due to blade icing and the cost of fighting this effect should also be further investigated besides the total costs of grid connection. Also other inaccuracies, concerning turbine price development, lifetime of the turbines and grid investments are recognised in the literature and can have a significant effect on the required tariff.

The NPV model is useful to assess the economical possibilities of wind power and calculate the required tariff support. Because of the relatively long lifetime of a turbine or wind park it may also lead to false conclusions. A high (10%) discount rate results in poor NPV for the last years of the lifetime, especially in models where electricity price is kept stable. If the aim is to compare the costs of onshore and offshore wind with each other or against other forms of power production, a more reasonable method would be the levelised cost of energy.

As this study indicates, the cost of offshore wind energy will be significantly higher compared to onshore turbines in Finland. An easy argument for offshore wind is that the industry is definitely not mature, and therefore a remarkable reduction in investment costs per rated power and in the cost of energy should be seen in the future. Other facts in favour of offshore turbines are the non-habituated space the turbines require, which can be easily found at sea, and higher average wind speeds compared to onshore locations.

The investment costs of offshore installations are still so much higher than onshore that greater production cannot compensate it. Our study indicates a feed-in tariff in the order of 115 €/MWh for 12 years to be required for economically viable projects to be started. This is in the same range as e.g. the recent offshore wind park support levels in Denmark (Horns Rev II: 69.5 €/MWh on top of the market price for 50,000 full load hours and Rødsand II: 84.4 €/MWh on top of the market price for 50,000 full load hours). However, Danish offshore farms are located in significantly less-severe climate conditions. The recent UK estimates [33] indicate slightly higher levelised cost estimates with a range of £100–£139 for offshore projects starting in 2013 conditions, using the same 10% discount rate as our study.

Engineering innovations in the industry give the possibilities for further development, but political willingness to pay defines the reality for the future of Finnish offshore wind. Public support for developing offshore wind in Finland would be justified also from the point of view of technology export opportunities. It is rather likely that there will be more offshore wind power development also in challenging cold climates. Therefore, developing offshore wind power operation in Finland could also increase expertise in this technology and provide future industrial export opportunities.

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